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Forward Osmosis Flow Rate Differential Using Different Osmotic Agents

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Cover Page Footnote

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Introduction

Life support is one of the most critical systems that supports manned spaceflight, but it is in its current state cumbersome and maintenance intensive. As the world begins to plan for longer duration missions beyond Earth’s orbit, the necessity of a sustainable life support system assumes an ever-greater importance. This is because the current systems are heavy, inefficient, and require regular expensive supply deliveries from Earth to function properly. Part of the reason for the inefficiency is due to the filtration systems used for scrubbing the air and cleaning water waste that primarily use mechanical pumping methods to pump through filtration mediums. These systems require heavy filters that must be regularly flown on resupply missions that are expensive and limiting to future mission objectives such as the long talked about manned mission to Mars. But instead of using the current crop of expensive and power-consuming methods of filtration, future long duration manned missions could use passive Forward Osmosis (FO) to filter water, thereby supporting necessary life support systems and at the same time increasing the degree of closure of the life support system.

Forward osmosis is a process of filtration that uses the natural principles of fluid concentration to pull clean water out of contaminated water. This is achieved by using a container divided by a FO membrane that has small pores in the micrometer range of diameter. Through these pores, water moves from a low concentrate contaminated solution into the high concentration “feed” solution. This method requires little to no electricity, pumping, or energy from the spacecraft. The only requirement is time for the system to filter nearly all the contaminated water into usable water.

Although there have been several experiments and proposed designs for FO-based life support systems, an efficient working model has yet to be produced. If a working model were to be produced, experiments would need to be conducted with efficiency and performance in mind so that the maximum amount of water could be filtered. The goal of this experiment, conducted in the life support system facility in the LUNARES habitat in Pila, Poland, was to quantify the efficiency of an osmotic agent between two agents (“feed solutions”) provided by the manufacturer of the FO filter bag.

Forward Osmosis

The process of filtration through forward osmosis (FO) is an emerging technology that uses membranes to filter the water with almost no external hydraulic pressure. The strength of this method is a function of the feed and draw solutions. These solutions consist of a feed solution with a low osmotic pressure and a draw solution with a high osmotic pressure. Osmotic pressure is driven by the concentration difference between the feed and draw solutions which pulls water from the feed solution into the higher concentrated draw solution through a semi-permeable membrane. This form of filtration is promising in the field of wastewater filtration as it fouls much less frequently compared with reverse osmosis systems (Linares, et al. 2014).

The filtration of water across the semi-permeable membrane is effective due to the water moving through the membrane leaving the contaminants in the feed solution. Although this process works with lower pressures than filtration methods such as reverse osmosis, fouling of the membrane does occur from buildup of contaminants in the feed water. Also, FO membranes can be cleaned so they can be reused for waste filtration. The Ames Research Center determined that after a near ten percent decrease in flow rate on a FO filter in water testing, the cleaning solution was able to return the flow rate to 96 percent of the maximum flow rate of the control clean test sample (Gamboa-Vázquez, Flynn, Romero-Mangado, & Parodi).

FO filtration has been tested in microgravity conditions. One experiment aboard Space Shuttle mission STS 135 consisted of a prepared feed and draw solution contained by a FO bag and tested at six and twelve hours samples via ion and flux analysis. This experiment showed that there was approximately a fifty percent decrease in flux rate in microgravity, but microgravity did not affect ion rejection. This testing also showed evidence of wicking (liquid sticking to the seams of the filtration bags in microgravity) which would make the process less efficient. This problem was resolved once a full charge of feed solution was applied (Flynn 2013).

Water Walls

The process of FO also lends itself to another potential future element of a life support system; Water Walls. Water Walls are a proposed system that represent a new approach to long duration life support. It applies the concepts of synthetic biology and microbiology along with the application of forward osmosis to establish a self-regulating life support system for future manned missions. Rather than relying on complex and maintenance-intensive mechanical equipment, the Water Walls approach comprises several simple systems that combine to perform all the functions of current life support systems (Cohen, Flynn, & Matossian 2012).

This proposed system is largely passive as it only requires small pumps and valves to move the water from module to module. It utilizes a modular system of FO filters and living microorganisms to takes gray water and convert it into usable water. The system would also be capable of managing other life support functions such as humidity and thermal control, blackwater processing, CO_2 removal and O_2 revitalization, moderate radiation shielding, and a nourishment production through the growth of edible microorganisms. This method of life support has been considered for use in upcoming long duration missions because of its passive nature since it doesn't require as much power as current active systems (Cohen, Flynn, & Matossian 2012) such as the International Space Station's Environmental Control and Life Support System (ECLSS) which uses mechanical systems in the Water Recovery System (WRS) and Oxygen Generation System (OGS) that are not only power draining, but also require intensive maintenance. This current life support system in use on the ISS is not suitable for long duration missions due to its need for consistent resupply of filters, replacement parts, and fresh water ("International Space Station Environmental Control and Life Support System." 2008).

Providing consistent resupply of material and consumables will not be possible on proposed long duration missions to Mars and other celestial destinations, hence the need for a life support system with a greater degree of closure. The advantage of the Water Walls system in this regard is that it allows for a near closed-loop functionality with its potential to take wastewater to provide fresh air and water as output. These functions will be achieved through the multiple layers of the Water Walls's modular architecture; Gray and black water waste enter the system where they are separated into solid waste and gray water liquid waste. The liquid waste can be filtered through the FO filters into either drinkable electrolyte drinks or could be filtered through a more efficient osmotic agent and then distilled in smaller amounts for drinking. The solid wastes can be broken down into a fertilizer for a cyanobacteria growth that would help filter the air of CO_2 and help regulate O_2 and N_2 levels in the air supply. Along with air scrubbing, this microbial life could be used as a nutritional supplement since some species are high in key nutrients that support astronaut health. The water used for these processes could also provide a natural barrier that could shield the spacecraft from harmful radiation during long duration space missions. This method was proposed as early as 1997 for crew habitats on missions to Mars but was deemed to be a parasitic mass that would be too inefficient to use as shielding due to its large mass. This mass can be attributed to the large mass of water necessary to reduce radiation to satisfactory levels. This would not be the case if the mass was instead being used for the life support systems of the module rather than strictly radiation shielding (Cohen, Flynn, & Matossian 2012).

In addition to being energy efficient for long duration missions, the Water Walls design is also "space" efficient. Recent models of the modular system show that it can be shaped into cellular bag modules that can be tessellated (Figure 1) along walls of cylindrical spacecrafts. This design would allow more room for astronauts and equipment in comparison to the current mechanical method for life support that requires a large amount of atmospheric control machinery and complex parts that require routine replacement (Cohen, Flynn, Matossian, & Mancinelli "Water Walls Life Support Architecture" 2013). The modular concept of Water Walls also allows for the inclusion of the evolving methods of life support and water filtration. One such developing method is the use of microalgae to treat wastewater. This system of tertiary treatment of water could augment the system to allow the pre- or post-treatment of the filtered water so that it could be used for further use. Using cyanobacteria this system can use solid wastes as a nitrogen source and carbon dioxide expelled by the crew in photosynthesis, releasing oxygen as a byproduct. This photosynthetic process would create a natural air scrubbing system that would not only treat the water, but also provide scrubbed breathable air for the crew to breathe (Abdel-Raouf, Al-Homaidan, & Ibraheem 2012).

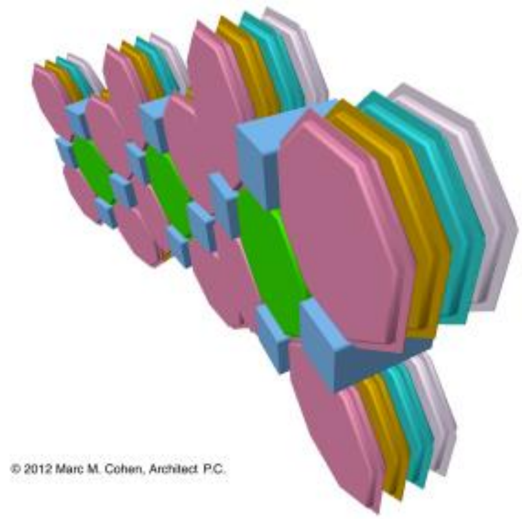

Figure 1: Tessellation of Water Walls (Cohen, Flynn, Matossian, & Mancinelli "Water Walls Life Support Architecture" 2013)

The goal of those designing the next generation of life support systems is to not only sustain human life in space, but to do so without the need for additional resources. This can only be achieved by increasing the degree of closure. At its core, a closed-loop life support system requires no introduced material from outside the "loop" to sustain it. It repurposes its own outputs into usable inputs to begin the cycle again. The use of this system has been attempted with some success in 1972 in the Siberian BIOS-3 bioregenerative life support experiments. These experiments consisted of an underground garden of oxygen-producing plants and microorganisms that filtered the CO_2 produced by the resident crew and turned it into breathable oxygen (Salisbury, Gitelson, & Lisovsky 1997). Although the BIOS-3 was unable to balance oxygen and food production in their life support system, the goal of future systems would be to balance all elements of human life support.

This goal of a perfectly balanced closed-loop life support system has to this day yet to be realized. Systems such as WW have been theorized to be able to self-sustain themselves, but in testing they are still in preliminary research phases. To reach physical prototyping, research will need to be done to determine the best methodology to produce the greatest amount of filtered water through the system. This research will provide a base to build a working life support system that could help astronauts reach to the edge of our solar system and beyond.

Methods

To test which FO feed solution produced higher and more consistent flowrate, a nutrient syrup solution and a salt brine solution were utilized due to their possible future uses in a life support system. The nutrient solution is the standard high concentration solution used for the commercially available FO filtration systems due to its high nutrient value when consumed in harsh environment. The salt brine was used due to the simplicity and availability that this solution would have in a life support system. These solutions were also the only readily available solutions that could come pre-prepared from Fluid Technology Solutions ($FTSH_2O$) the manufacturer of the FO filtration bags. The specific ingredients of the solutions are listed in Table 1.

Table 1: Feed solution contents for Syrup and Brine solutions.

Nutrient Syrup Feed Solution	**Salt Brine Feed Solution**
Dextrose, Fructose, Malic Acid, Potassium Sodium Tartrate, Sodium Benzoate, Salt (NaCl), Monopotassium Phosphate, Grape Extract	28% Solution NaCl

A. Materials

Ingredients of the feed solutions used in this experiment are described in Table 1. Figure 2 is provided as a reference overview of the hardware discussed herein. The main piece of equipment in the experiment was the FO filtration bag. The model utilized in the experiment was the HighSeas™ system purchased from $FTSH_2O$.

B. Methods

System Operation

This filtration systems work on the principal of Forward Osmosis. This process, as discussed in the above introduction, utilizes concentration gradients across a sei-permeable membrane. The FO filtrations bags are two chambered vessels separated by a FO membrane. This system was designed by the manufacturer to be a survival filtration system for people trapped on the ocean or in situations without clean water. To use the system, contaminated water is filled into the red capped chamber and the osmotic feed solution is poured into the green capped chamber. The system is then set for 8 hours for osmotic pressure to pull the water from the contaminated chamber through the membrane into the feed solution. Once the process is complete the filtered water is safe to consume.

Set Up

The experiment was divided into 3 categories of equipment: Filtration system bags, Hanging Rack, and Syringes. One filter bag was used for each feed solution and labeled either “SALT” or “SYRUP”. The hanging rack was set up to reflect the design shown in Figure 1. The syringes were separated, labeled, and sterilized. They were labeled as “CLEAN”, “WASTE”, and “EXCESS”. This set up and the parts of the FO bag are shown in Figure 2.

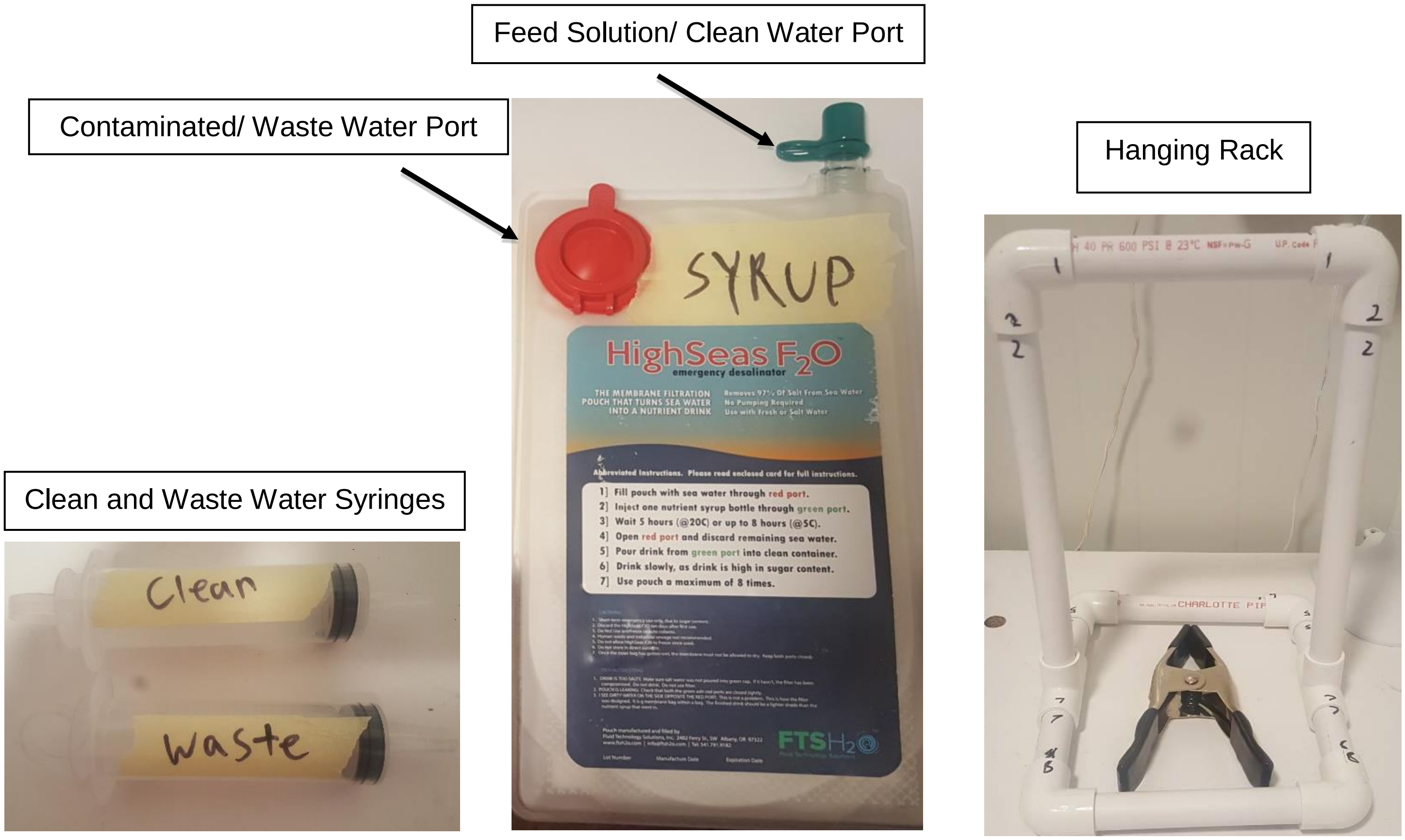

Figure 2: Parts of FO bag / Equipment

Conducting the Experiment

Step 1: The hanging rack (Figure 2) was assembled, and the empty FO bags hung up on it.

Step 2: The contaminated water side of the bag was filled with 1 L of water using the 100 mL syringe labeled “WASTE”. This was injected via the red waste port of the bag (Figure 2).

Step 3: A 85mL bottle of feed solution was poured into the feed side of the correct bag that correlated with the osmotic agent type via the feed/ clean water port (Figure 2).

Step 4: The FO bags were then left hanging on the hanging rack for 8 hours as shown in Figure 3.

Step 5: The filtered water solution was then poured into labeled storage containers for volume measurement.

Step 6: The remaining contaminated water was removed from the red waste port (Figure 1) with the syringe labeled “EXCESS” and disposed.

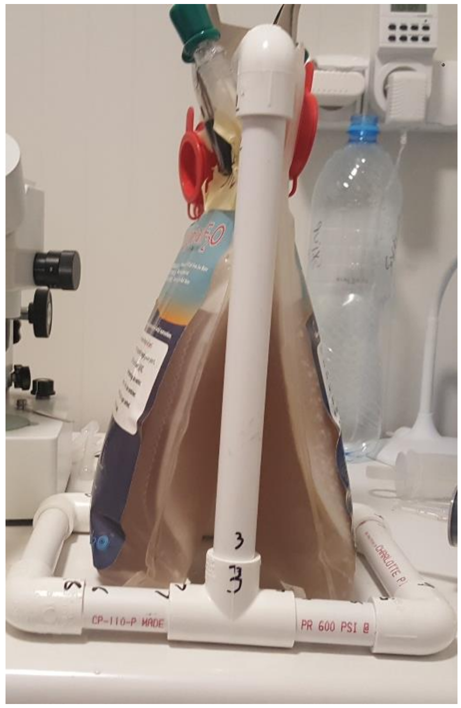

Figure 3: Set up of FO bags during testing

Data Analysis

A key element to establish the difference in efficiency and performance of the osmotic agents was analysis of the flow rate. Flow rates of the salt brine and the nutrient syrup feed solutions were measured to evaluate performance in milliliters per hour (mL/h) of water filtered. Using a graduated cylinder, the contaminated water before filtration and the filtered water collected in the 8-hour time frame were measured in milliliters to determine an average filtered amount. This amount was then divided by the time frame to determine flow rate in mL/h. The flow rates of the two types of feed solutions were then compared to determine performance differences between them. Along with this average flow rate, a standard deviation of the data was determined to show which of the agents exhibit a lower deviation and had more consistent results over time.

Results

Flow Rate

When the filtered water was measured after the 8 hours filtration period, the volume of the filtered water was measured against the unfiltered water in the FO bag. There were 5 trials conducted on each of the FO filtration bags to establish accurate volume and flow rate data. The averages and standard deviation of this data are presented in Table 2. Although the difference in the averages is small at 31.7 mL, the salt agent filtered 3.895% more water than the syrup solution.

Table 2: Trial Data of the Volume of Filtered Water after 8 hrs. Syrup is the Nutrient Syrup Feed Solution. Salt is the Salt Brine Feed Solution.

FO Feed Solution	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5
Syrup	913 L	1063 L	1005 L	997 L	1019 L
Salt	1110 L	1007 L	1008 L	1048 L	1023 L

Table 3: Average and Standard Deviation of the Flow data. Syrup is the Nutrient Syrup Feed Solution. Salt is the Salt Brine Feed Solution.

FO Feed Solution	Average Filtered Volume	Standard Deviation of Filtered Volume	Average Flowrate (mL/h)	Standard Deviation of Flowrate
Syrup	999.4 mL	54.615	124.925 mL/h	6.827
Salt	1039.2 mL	42.903	129.886 mL/h	5.337

Discussion

The FO flow rate experiment demonstrates the salt feed solution’s slight performance advantage over a sugar-based nutrient syrup feed solution. Although the salt feed solution preformed slightly better in this experiment, a t-test on that dara shows that in this sample it is not a statistically significant difference in average. All the filtration bags performed as expected and filtered water was produced. The experiment procedures worked well for the flowrate comparison experiment. Feedback from colleagues assisting experimentation in the LUNARES habitat noted that the procedures functioned well without any notable issues.

The experiment data demonstrated a high level of variability, which could indicate a source of experimental error due to a low level of trials and thus a small pool of data to analyze. The experiment will need to be revisited with expanded procedures and additional experiment objectives to collect data that can be used to further optimize the use of the FO filtration bags.

Future Experiments

The goal of this experiment and future trials are to explore FO filtration and discover if the process can be made to work at its highest efficiency. The results of this experiment were a starting point from which future experiments can be designed to expand of a number of possible methods to increase the efficiency of the FO system.

Some of the variability of the results could have been caused by fouling in the membrane pores by solid contaminates that were in the waste. This fouling could be marginalized by having filter cleaning procedures between each trial to clear any fouling in the membrane pores. More consistent results could possibly be achieved with these cleaning procedures in place. During further trials of this experiment, comparison results could be gathered to show whether or not these procedures effect flowrate.

Weight restrictions during travel to Poland allowed for only two FO filtration bags to be brought abroad for the experiment and, due to time restrictions during the research expedition to the LUNARES habitat, only five trials were able to be conducted during the expedition. Additional data could be gathered through further experimentation using multiple FO filtration bags with the same solution being tested at the same time. Although each bag can only sustain eight trials before the filtration membrane begins to deteriorate, the experiment could use two or more FO filtration bags at a time for each solution per trial to create a larger data set. This data could be used to establish more accurate averages and trends in the data.

A factor of the filtration process that was not explored in this experiment was the quality of the filtration of the water that was removed from the FO filter bag. Future experiments in a better equipped laboratory for toxicological research testing could provide quality comparison between the two feed solutions explored in this experiment. These experiments could also explore what quality of water is produced, and what purposes that water could serve in a life support system. This test of quality is key to the eventual use of FO as a filtration system for drinking water in human spaceflight missions.

The goal of these future experiments would be to optimize the filtration using FO and eventually implement it into a complete life support system. Water Wall systems could receive the most benefit from FO becoming a more efficient and optimized filtration system because the majority of the Water Wall system is passively run, and the pressure necessary to run this system could be provided by osmotic pressure filtering water from one chamber of a specific concentration of solution into the next.

By showing that there is a measurable difference in flow due to the use of different osmotic agents, this experiment has shown the potential to increase the efficiency of the FO process and expand on this emerging field of life support science. Future optimization experiments can be used to build the backbone for a functional concept of the proposed Water Wall life support technology. This endeavor is one that could be undertaken over the course of multiple experiments that individually optimize each subsystem of the Water Wall so that they can be used together for their intended collective purpose of providing long-term and low maintenance life support for future deep space manned missions to Mars and beyond.

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